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SUPERFUND RECORDS

## Development and Evaluation of Consensus-Based Sediment Quality Guidelines for Freshwater Ecosystems

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Received: 23 August 1999/Accepted: 13 January 2000

**Abstract.** Numerical sediment quality guidelines (SQGs) for freshwater ecosystems have previously been developed using a variety of approaches. Each approach has certain advantages and limitations which influence their application in the sediment quality assessment process. In an effort to focus on the agreement among these various published SQGs, consensus-based SQGs were developed for 28 chemicals of concern in freshwater sediments (*i.e.*, metals, polycyclic aromatic hydrocarbons, polychlorinated biphenyls, and pesticides). For each contaminant of concern, two SQGs were developed from the published SQGs, including a threshold effect concentration (TEC) and a probable effect concentration (PEC). The resultant SQGs for each chemical were evaluated for reliability using matching sediment chemistry and toxicity data from field studies conducted throughout the United States. The results of this evaluation indicated that most of the TECs (*i.e.*, 21 of 28) provide an accurate basis for predicting the absence of sediment toxicity. Similarly, most of the PECs (*i.e.*, 16 of 28) provide an accurate basis for predicting sediment toxicity. Mean PEC quotients were calculated to evaluate the combined effects of multiple contaminants in sediment. Results of the evaluation indicate that the incidence of toxicity is highly correlated to the mean PEC quotient ( $R^2 = 0.98$  for 347 samples). It was concluded that the consensus-based SQGs provide a reliable basis for assessing sediment quality conditions in freshwater ecosystems.

Numerical sediment quality guidelines (SQGs; including sediment quality criteria, sediment quality objectives, and sediment quality standards) have been developed by various federal, state, and provincial agencies in North America for both freshwater and marine ecosystems. Such SQGs have been used in numerous applications, including designing monitoring programs, interpreting historical data, evaluating the need for detailed sediment quality assessments, assessing the quality of

prospective dredged materials, conducting remedial investigations and ecological risk assessments, and developing sediment quality remediation objectives (Long and MacDonald 1998). Numerical SQGs have also been used by many scientists and managers to identify contaminants of concern in aquatic ecosystems and to rank areas of concern on a regional or national basis (*e.g.*, US EPA 1997a). It is apparent, therefore, that numerical SQGs, when used in combination with other tools, such as sediment toxicity tests, represent a useful approach for assessing the quality of freshwater and marine sediments (MacDonald *et al.* 1992; US EPA 1992, 1996a, 1997a; Adams *et al.* 1992; Ingersoll *et al.* 1996, 1997).

The SQGs that are currently being used in North America have been developed using a variety of approaches. The approaches that have been selected by individual jurisdictions depend on the receptors that are to be considered (*e.g.*, sediment-dwelling organisms, wildlife, or humans), the degree of protection that is to be afforded, the geographic area to which the values are intended to apply (*e.g.*, site-specific, regional, or national), and their intended uses (*e.g.*, screening tools, remediation objectives, identifying toxic and not-toxic samples, bioaccumulation assessment). Guidelines for assessing sediment quality relative to the potential for adverse effects on sediment-dwelling organisms in freshwater systems have been derived using a combination of theoretical and empirical approaches, primarily including the equilibrium partitioning approach (EqPA; Di Toro *et al.* 1991; NYSDEC 1994; US EPA 1997a), screening level concentration approach (SLCA; Persaud *et al.* 1993), effects range approach (ERA; Long and Morgan 1991; Ingersoll *et al.* 1996), effects level approach (ELA; Smith *et al.* 1996; Ingersoll *et al.* 1996), and apparent effects threshold approach (AETA; Cabbage *et al.* 1997). Application of these methods has resulted in the derivation of numerical SQGs for many chemicals of potential concern in freshwater sediments.

Selection of the most appropriate SQGs for specific applications can be a daunting task for sediment assessors. This task is particularly challenging because limited guidance is currently available on the recommended uses of the various SQGs. In addition, the numerical SQGs for any particular substance can differ by several orders of magnitude, depending on the derivation procedure and intended use. The SQG selection process is further complicated due to uncertainties regarding

Table 1. Descriptions of the published freshwater SQGs that have been developed using various approaches

Type of SQG	Acronym	Approach	Description	Reference
<u>Threshold effect concentration SQGs</u>				
Lowest effect level	LEL	SLCA	Sediments are considered to be clean to marginally polluted. No effects on the majority of sediment-dwelling organisms are expected below this concentration.	Persaud <i>et al.</i> (1993)
Threshold effect level	TEL	WEA	Represents the concentration below which adverse effects are expected to occur only rarely.	Smith <i>et al.</i> (1996)
Effect range—low	ERL	WEA	Represents the chemical concentration below which adverse effects would be rarely observed.	Long and Morgan (1991)
Threshold effect level for <i>Hyaella azteca</i> in 28-day tests	TEL-HA28	WEA	Represents the concentration below which adverse effects on survival or growth of the amphipod <i>Hyaella azteca</i> are expected to occur only rarely (in 28-day tests).	US EPA (1996a); Ingersoll <i>et al.</i> (1996)
Minimal effect threshold	MET	SLCA	Sediments are considered to be clean to marginally polluted. No effects on the majority of sediment-dwelling organisms are expected below this concentration.	EC and MENVIQ (1992)
Chronic equilibrium partitioning threshold	SQAL	EqPA	Represents the concentration in sediments that is predicted to be associated with concentrations in the interstitial water below a chronic water quality criterion. Adverse effects on sediment-dwelling organisms are predicted to occur only rarely below this concentration.	Bolton <i>et al.</i> (1985); Zarba (1992); US EPA (1997a)
<u>Probable effect concentration SQGs</u>				
Severe effect level	SEL	SLCA	Sediments are considered to be heavily polluted. Adverse effects on the majority of sediment-dwelling organisms are expected when this concentration is exceeded.	Persaud <i>et al.</i> (1993)
Probable effect level	PEL	WEA	Represents the concentration above which adverse effects are expected to occur frequently.	Smith <i>et al.</i> (1996)
Effect range—median	ERM	WEA	Represents the chemical concentration above which adverse effects would frequently occur.	Long and Morgan (1991)
Probable effect level for <i>Hyaella azteca</i> in 28-day tests	PEL-HA28	WEA	Represents the concentration above which adverse effects on survival or growth of the amphipod <i>Hyaella azteca</i> are expected to occur frequently (in 28-day tests).	US EPA (1996a); Ingersoll <i>et al.</i> (1996)
Toxic effect threshold	TET	SLCA	Sediments are considered to be heavily polluted. Adverse effects on sediment-dwelling organisms are expected when this concentration is exceeded.	EC and MENVIQ (1992)

and Waukegan Harbor, IL (US EPA 1996a; Kemble *et al.* 1999). These studies provided 17 data sets (347 sediment samples) with which to evaluate the predictive ability of the SQGs. These studies also represented a broad range in both sediment toxicity and contamination; roughly 50% of these samples were found to be toxic based on the results of the various toxicity tests (the raw data from these studies are summarized in Ingersoll and MacDonald 1999).

In the second step of the evaluation, the measured concentration of each substance in each sediment sample was compared to the corresponding SQG for that substance. Sediment samples were predicted to

be not toxic if the measured concentrations of a chemical substance were lower than the corresponding TEC. Similarly, samples were predicted to be toxic if the corresponding PECs were exceeded in field-collected sediments. Samples with contaminant concentrations between the TEC and PEC were neither predicted to be toxic nor nontoxic (*i.e.*, the individual SQGs are not intended to provide guidance within this range of concentrations). The comparisons of measured concentrations to the SQGs were conducted for each of the 28 chemicals of concern for which SQGs were developed.

In the third step of the evaluation, the accuracy of each prediction

Table 3. Sediment quality guidelines for metals in freshwater ecosystems that reflect PECs (*i.e.*, above which harmful effects are likely to be observed)

Substance	Probable Effect Concentrations					Consensus-Based PEC ✓
	PEL ✓	SEL ✓	TET	ERM ✓	PEL-HA28	
Metals (in mg/kg DW)						
Arsenic	17	33	17	85	48	33.0
Cadmium	3.53	10	3	9	3.2	4.98
Chromium	90	110	100	145	120	111
Copper	197	110	86	390	100	149
Lead	913	250	170	110	82	128
Mercury	0.486	2	1	1.3	NG	1.06
Nickel	36	75	61	50	33	48.6
Zinc	315	820	540	270	540	459
Polycyclic aromatic hydrocarbons (in µg/kg DW)						
Anthracene	NG	3,700	NG	960	170	845
Fluorene	NG	1,600	NG	640	150	536
Naphthalene	NG	NG	600	2,100	140	561
Phenanthrene	515	9,500	800	1,380	410	1,170
Benz[a]anthracene	385	14,800	500	1,600	280	1,050
Benzo(a)pyrene	782	14,400	700	2,500	320	1,450
Chrysene	862	4,600	800	2,800	410	1,290
Fluoranthene	2,355	10,200	2,000	3,600	320	2,230
Pyrene	875	8,500	1,000	2,200	490	1,520
Total PAHs	NG	100,000	NG	35,000	3,400	22,800
Polychlorinated biphenyls (in µg/kg DW)						
Total PCBs	277	5,300	1,000	400	240	676
Organochlorine pesticides (in µg/kg DW)						
Chlordane	8.9	60	30	6	NG	17.6
Dieldrin	6.67	910	300	8	NG	61.8
Sum DDD	8.51	60	60	20	NG	28.0
Sum DDE	6.75	190	50	15	NG	31.3
Sum DDT	NG	710	50	7	NG	62.9
Total DDTs	4,450	120	NG	350	NG	572
Endrin	62.4	1,300	500	45	NG	207
Heptachlor Epoxide	2.74	50	30	NG	NG	16.0
Lindane (gamma-BHC)	1.38	10	9	NG	NG	4.99

PEL = Probable effect level; dry weight (Smith *et al.* 1996) *Canada*  
 SEL = Severe effect level, dry weight (Persaud *et al.* 1993) *ONTARIO*  
 TET = Toxic effect threshold; dry weight (EC and MENVIQ 1992)  
 ERM = Effect range median; dry weight (Long and Morgan 1991)  
 PEL-HA28 = Probable effect level for *Hyaella azteca*; 28-day test; dry weight (US EPA 1996a)  
 NG = No guideline

not unduly influenced by the number of sediment samples available to conduct the evaluation of predictive ability, the various SQGs were considered to be reliable only if a minimum of 20 samples were included in the predictive ability evaluation (CCME 1995).

The initial evaluation of predictive ability was focused on determining the ability of each SQG when applied alone to classify samples correctly as toxic or nontoxic. Because field-collected sediments typically contain complex mixtures of contaminants, the predictability of these sediment quality assessment tools is likely to increase when the SQGs are used together to classify these sediments. For this reason, a second evaluation of the predictive ability of the SQGs was conducted to determine the incidence of effects above and below various mean PEC quotients (*i.e.*, 0.1, 0.5, 1.0, and 1.5). In this evaluation, mean PEC quotients were calculated using the methods of Long *et al.* (1998; *i.e.*, for each sediment sample, the average of the ratios of the concentration of each contaminant to its corresponding PEC was calculated for each sample), with only the PECs that were found to be reliable used in these calculations. The PEC for total PAHs (*i.e.*,

instead of the PECs for the individual PAHs) was used in the calculation to avoid double counting of the PAH concentration data.

## Results and Discussion

### Derivation of Consensus-Based SQGs

A variety of approaches have been developed to support the derivation of numerical SQGs for the protection of sediment-dwelling organisms in the United States and Canada. MacDonald (1994), Ingersoll and MacDonald (1999), and MacDonald *et al.* (2000) provided reviews of the various approaches to SQG development, including descriptions of the derivation methods, the advantages and limitations of the resultant SQGs, and their recommended uses. This information,

Table 4. Predictive ability of the consensus-based TECs in freshwater sediments

Substance	Number of Samples Evaluated	Number of Samples Predicted to Be Not Toxic	Number of Samples Observed to Be Not Toxic	Percentage of Samples Correctly Predicted to Be Not Toxic
<b>Metals</b>				
Arsenic	150	58	43	74.1
Cadmium	347	102	82	80.4
Chromium	347	132	95	72.0
Copper	347	158	130	82.3
Lead	347	152	124	81.6
Mercury	79	35	12	34.3
Nickel	347	184	133	72.3
Zinc	347	163	133	81.6
<b>Polycyclic aromatic hydrocarbons</b>				
Anthracene	129	75	62	82.7
Fluorene	129	93	66	71.0
Naphthalene	139	85	64	75.3
Phenanthrene	139	79	65	82.3
Benz(a)anthracene	139	76	63	82.9
Benzo(a)pyrene	139	81	66	81.5
Chrysene	139	80	64	80.0
Dibenz(a,h)anthracene	98	77	56	72.7
Fluoranthene	139	96	72	75.0
Pyrene	139	78	62	79.5
Total PAHs	167	81	66	81.5
<b>Polychlorinated biphenyls</b>				
Total PCBs	120	27	24	88.9
<b>Organochlorine pesticides</b>				
Chlordane	193	101	86	85.1
Dieldrin	180	109	91	83.5
Sum DDD	168	101	81	80.2
Sum DDE	180	105	86	81.9
Sum DDT	96	100	77	77.0
Total DDT	110	92	76	82.6
Endrin	170	126	89	70.6
Heptachlor epoxide	138	90	74	82.2
Lindane	180	121	87	71.9

were established in this study (Table 5). Among the seven individual trace metals, the predictive ability of the PECs ranged from 77% for arsenic to 94% for cadmium. The PECs for six individual PAHs and total PAHs were also demonstrated to be reliable, with predictive abilities ranging from 92% to 100%. The predictive ability of the PEC for total PCBs was 82%. While the PEC for Sum DDE was also found to be an accurate predictor of sediment toxicity (*i.e.*, predictive ability of 97%), the predictive ability of the PEC for chlordane was somewhat lower (*i.e.*, 73%). Therefore, the consensus-based PECs for arsenic, cadmium, chromium, copper, lead, nickel, zinc, naphthalene, phenanthrene, benz[a]anthracene, benzo(a)pyrene, chrysene, pyrene, total PAHs, total PCBs, and sum DDE provide an accurate basis for predicting toxicity in freshwater sediments from numerous locations in North America (*i.e.*, predictive ability of  $\geq 75\%$ ; Table 5). Insufficient data were available (*i.e.*, fewer than 20 samples predicted to be toxic) to evaluate the PECs for mercury, anthracene, fluorene, fluoranthene, dieldrin, sum DDD, sum DDT, total DDT, endrin, heptachlor epoxide, and lindane (Table 5).

The two types of SQGs define three ranges of concentrations for each chemical substance. It is possible to assess the degree of concordance that exists between chemical concentrations and the incidence of sediment toxicity (Table 6; MacDonald *et al.* 1996)

by determining the ratio of toxic samples to the total number of samples within each of these three ranges of concentrations for each substance. The results of this evaluation demonstrate that, for most chemical substances (*i.e.*, 20 of 28), there is a consistent and marked increase in the incidence of toxicity to sediment-dwelling organisms with increasing chemical concentrations. For certain substances, such as naphthalene, mercury, chlordane, dieldrin, and sum DDD, a lower PEC may have produced greater concordance between sediment chemistry and the incidence of effects. Insufficient data were available to evaluate the degree of concordance for several substances, such as endrin, heptachlor epoxide, and lindane. The positive correlation between contaminant concentrations and sediment toxicity that was observed increases the degree of confidence that can be placed in the SQGs for most of the substances.

While the SQGs for the individual chemical substances provide reliable tools for assessing sediment quality conditions, predictive ability should be enhanced when used together in assessments of sediment quality. In addition, it would be helpful to consider the magnitude of the exceedances of the SQGs in such assessments. Long *et al.* (1998) developed a procedure for evaluating the biological significance of contaminant mixtures through the application of mean PEC quotients. A three-

Table 6. Incidence of toxicity within ranges of contaminant concentrations defined by the SQGs

Substance	Number of Samples Evaluated	Incidence of Toxicity (% , number of samples in parentheses)			
		≤TEC	TEC-PEC	> PEC	
<i>Metals</i>					
Arsenic	150	25.9% (15 of 58)	57.6% (38 of 66)	76.9% (20 of 26)	
Cadmium	347	19.6% (20 of 102)	44.6% (29 of 65)	93.7% (19 of 20)	
Chromium	347	28% (37 of 132)	64.4% (38 of 59)	91.7% (100 of 109)	
Copper	347	17.7% (28 of 158)	64.0% (48 of 75)	91.8% (101 of 110)	
Lead	347	18.4% (28 of 152)	53.6% (37 of 69)	89.6% (112 of 125)	
Mercury	79	65.7% (23 of 35)	70.0% (28 of 40)	100% (4 of 4)	
Nickel	347	27.7% (51 of 184)	62.7% (32 of 51)	90.6% (87 of 96)	
Zinc	347	18.4% (30 of 163)	60.9% (39 of 64)	90.0% (108 of 120)	
<i>Polycyclic aromatic hydrocarbons</i>					
Anthracene	129	17.3% (13 of 75)	92.9% (26 of 28)	100% (13 of 13)	
Fluorene	129	29% (27 of 93)	85.7% (12 of 14)	100% (13 of 13)	
Naphthalene	139	24.7% (21 of 85)	94.1% (16 of 17)	92.3% (24 of 26)	
Phenanthrene	139	17.7% (14 of 79)	88.2% (30 of 34)	100% (25 of 25)	
Benz(a)anthracene	139	17.1% (13 of 76)	70% (14 of 20)	100% (20 of 20)	
Benzo(a)pyrene	139	18.5% (15 of 81)	75.7% (28 of 37)	100% (24 of 24)	
Chrysene	139	20% (16 of 80)	68.1% (32 of 47)	95.8% (23 of 24)	
Fluoranthene	139	25% (24 of 96)	82.5% (33 of 40)	100% (15 of 15)	
Pyrene	139	20.5% (16 of 78)	63.0% (29 of 46)	96.4% (27 of 28)	
Total PAHs	167	18.5% (15 of 81)	65.1% (43 of 66)	100% (20 of 20)	
<i>Polychlorinated biphenyls</i>					
Total PCBs	120	11.1% (3 of 27)	31.0% (9 of 29)	82.3% (42 of 51)	
<i>Organochlorine pesticides</i>					
Chlordane	193	14.9% (15 of 101)	75.0% (15 of 20)	73.0% (27 of 37)	
Dieldrin	180	16.5% (18 of 109)	95.2% (20 of 21)	100% (10 of 10)	
Sum DDD	168	19.8% (20 of 101)	33.3% (1 of 3)	83.3% (5 of 6)	
Sum DDE	180	18.1% (19 of 105)	33.3% (1 of 3)	96.7% (29 of 30)	
Sum DDT	96	23% (23 of 100)	0.0% (0 of 1)	91.7% (11 of 12)	
Total DDT	110	17.4% (16 of 92)	100% (23 of 23)	100% (10 of 10)	
Endrin	170	29.4% (37 of 126)	40.0% (4 of 10)	NA% (0 of 0)	
Heptachlor epoxide	138	17.8% (16 of 90)	85.0% (17 of 20)	37.5% (3 of 8)	
Lindane	180	28.1% (34 of 121)	65.9% (29 of 44)	82.4% (14 of 17)	

Table 7. Predictive ability of mean PEC quotients in freshwater sediments

Mean PEC Quotient	Mean PEC Quotients Calculated with Total PAHs Predictive Ability (%)	Mean PEC Quotients Calculated with Individual PAH Predictive Abilities (%)
<0.1	90.2% (61)	90.2% (61)
<0.5	82.8% (174)	82.9% (175)
>0.5	85% (173)	85.4% (172)
>1.0	93.3% (143)	93.4% (143)
>1.5	94.4% (125)	95% (121)

threshold that can be used to accurately classify sediment samples as both toxic and not toxic. The results of this evaluation were not substantially different when the PECs for the individuals PAHs (*i.e.*, instead of the PEC for total PAHs) were used to calculate the mean PEC quotients (Table 7). Kemble *et al.* (1999) reported similar results when the mean PEC quotients were evaluated using the results of only 28-day toxicity tests with *H. azteca* ( $n = 149$ , 32% of the samples were toxic).

To examine further the relationship between the degree of chemical contamination and probability of observing toxicity

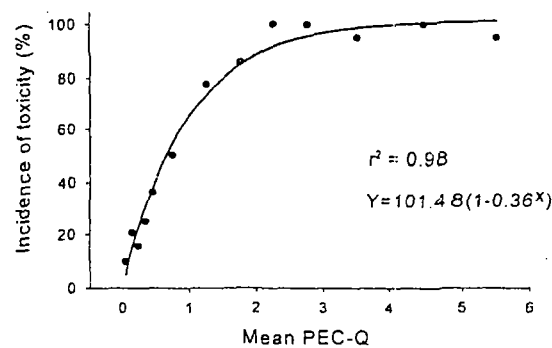


Fig. 1. Relationship between mean PEC quotient and incidence of toxicity in freshwater sediments

in freshwater sediments, the incidence of toxicity within various ranges of mean PEC quotients was calculated (*e.g.*, < 0.1, 0.1–0.2, 0.2–0.3). Next, these data were plotted against the midpoint of each range of mean PEC quotients (Figure 1). Subsequent curve-fitting indicated that the mean PEC-quotient is highly correlated with incidence of toxicity ( $r^2 = 0.98$ ), with the relationship being an exponential function. The resultant

organisms. The PEC quotients should be used to assess sediment that contain complex mixtures of chemical contaminants.

The consensus-based SQGs described in this paper do not consider the potential for bioaccumulation in aquatic organisms nor the associated hazards to the species that consume aquatic organisms (*i.e.*, wildlife and humans). Therefore, it is important to use the consensus-based SQGs in conjunction with other tools, such as bioaccumulation-based SQGs, bioaccumulation tests, and tissue residue guidelines, to evaluate more fully the potential effects of sediment-associated contaminants in the environment. Future investigations should focus on evaluating the predictive ability of these sediment assessment tools on a species- and endpoint-specific basis for various geographic areas.

**Acknowledgments.** The authors would like to acknowledge a number of individuals who have contributed to the production of this manuscript, including Ed Long, Jay Field (National Oceanic and Atmospheric Administration), Nile Kemble, Ning Wang (U.S. Geological Survey), Corinne Severn (EVS Environment Consultants), Jim Dwyer (U.S. Fish and Wildlife Service), and Rebekka Lindscoog and Mary Lou Haines (MacDonald Environmental Sciences Ltd.). The authors would also like to acknowledge Dan Sparks (U.S. Fish and Wildlife Service), Michael Macfarlane (B.C. Ministry of the Environment), and two anonymous reviewers for conducting thorough peer reviews of this manuscript. The preparation of this paper was supported in part by funding provided by the U.S. Department of Justice (USDOJ) and the National Research Council of Canada (NRCC). The views expressed herein are those of the authors and do not necessarily reflect the views of USDOJ or USGS.

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